Nuclear Cross Sections for Space Radiation Applications

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OUTLINE

- Space Radiation Environment
- Lippmann-Schwinger Equation
- Interaction and Parameterizations
- Models
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- Conclusions

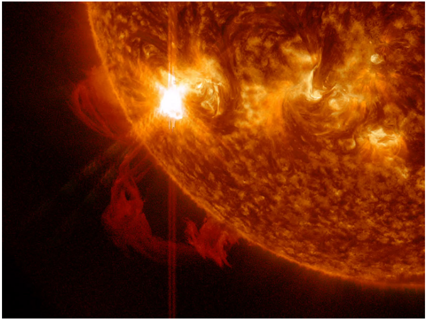
Introduction

- Space Radiation Environment

Galactic Cosmic Rays

Hubble Space Telescope

Solar Particle Events



Solar Dynamics Observatory

- Accurate cross sections are needed for radiation transport

Lippmann-Schwinger Equation

- Lippmann-Schwinger Equation: $T = V + VG_0^+ T$
- For elastic scattering, use equivalent set of coupled equations
  - Elastic Scattering Equation:

$$T = U + UPG_0^+ PT$$

  - Optical Potential:

$$U = V + VQG_0^+ QU$$

- Elastic scattering equation in momentum-space

$$T(\mathbf{k}', \mathbf{k}) = U(\mathbf{k}', \mathbf{k}) + \int U(\mathbf{k}', \mathbf{k}'') G_0^+(k'', k) T(\mathbf{k}'', \mathbf{k}) d\mathbf{k}''$$

where

$$G_0^+(k'', k) = \frac{1}{E(k) - E(k'') + i\eta}$$

Interaction

- Potential is sum of nucleon-nucleon (NN) interactions

$$V = \sum_{i=1}^{A_P} \sum_{j=1}^{A_T} v_{ij}$$

- Write series in terms of pseudo two-body operators

$$U_{ij} = \tau_{ij} + \tau_{ij} Q G_0^{+} Q \sum_{lm} U_{lm}$$

where

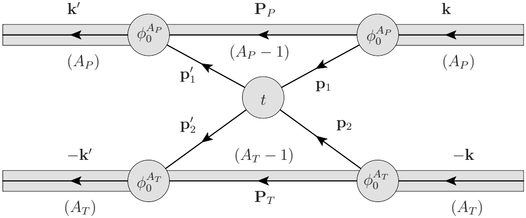
$$\tau_{ij} = v_{ij} + v_{ij} Q G_0^{+} Q \tau_{ij}$$

- Express τ_{ij} in terms of t_{ij}

$$\tau_{ij} = t_{ij} + t_{ij} (Q G_0^{+} Q - g) \tau_{ij}$$

Interaction

Nucleus-Nucleus Scattering



- Impulse approximation: $\tau_{ij} \to t_{ij}$
- Single Scattering
- Optimum Factorization
- Transition amplitude evaluated at beam energy for central potentials

$$U(\mathbf{k}', \mathbf{k}) = A_P A_T \eta t_{\mathrm{NN}}(q, \epsilon) \rho_T(q) \rho_P(q)$$

Parameterizations

- Nuclear Matter Density
  - For $A \leq 16$, Harmonic-Well Model[1]
  - For $A > 16$, Two parameter Fermi Model[1]
  - If no data for $A \leq 16$, isotopic average of parameters is used
  - If no data for $A > 16$, Nuclear Droplet Model[2] is used
- NN transition amplitude[3]
  - Cross sections
  - Real to imaginary ratio
  - Slope parameters

[1] De Vries et al. Atom. Nucl. Data **14**, 479 (1974); De Vries et al. Atom. Nucl. Data **36**, 495 (1987)
[2] Ann. Phys. **84**, 186 (1974)
[3] Werneth et al. NASA Technical Publication 2014-218529

Models

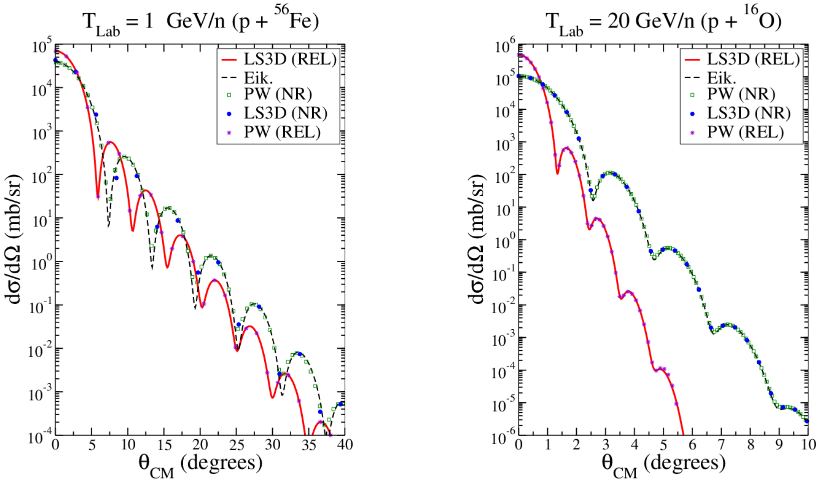
- Eikonal (Eik)
  - High Energy, Forward Scattering
  - Non-relativistic
- Partial Wave (PW)
  - Relativistic kinematics easily incorporated
  - Partial wave decomposition is an approximation
  - Numerically unstable for large number of partial wave
  - Finite summation formulas were implemented[4]
- Three-Dimensional Lippmann-Schwinger[5] (LS3D)
  - Relativistic kinematics easily incorporated
  - Not an approximation
  - Extended to reactions relevant for space radiation applications[6]

[4] Werneth et al. Nucl. Instr. Meth. B **308**, 40 (2013)

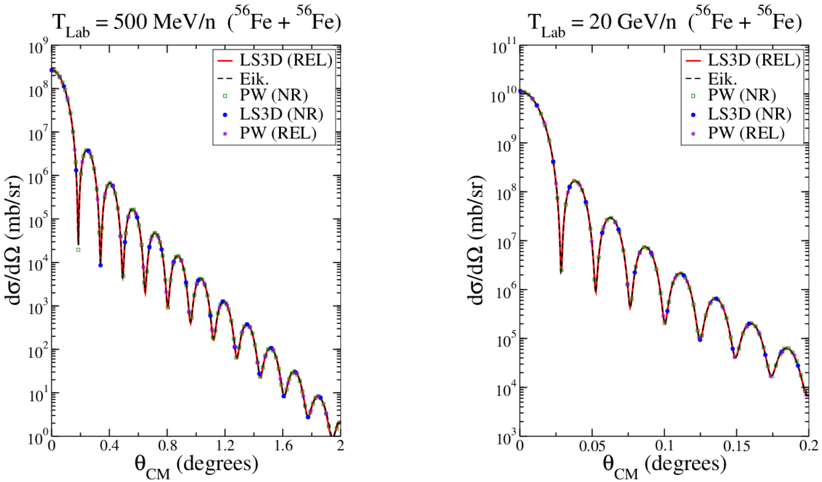
[5] Ch. Elster et al. Few-Body-Syst. **24** 55 (1998); M. Rodriguez-Gallardo et al. Phys. Rev. C **78** 034602 (2008)

[6] Werneth et al. Phys. Rev. C **90**, 064905 (2014); Werneth et al. NASA Technical-Publication 2014-218529

Unequal Mass Comparisons

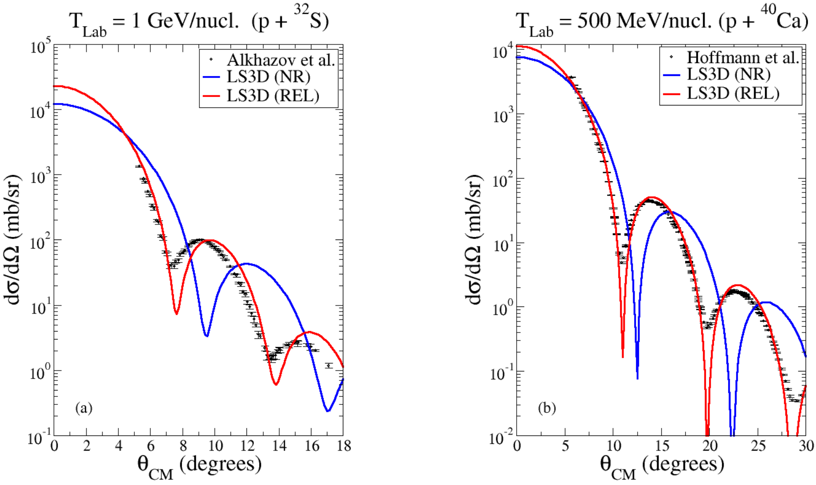


Equal Mass Reactions



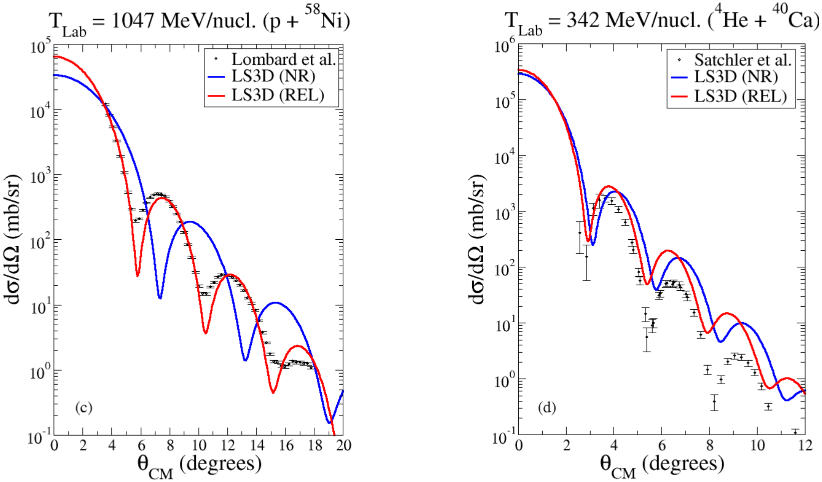
- Equal mass results explained with rapidly decaying potential in Werneth et al. Phys. Lett. B **749** 331 (2015)

Comparison to Experiment



- Results communicated in Werneth et al. Phys. Rev. C **90** 064905 (2014)

Comparison to Experiment



- Results communicated in Werneth et al. Phys. Rev. C **90** 064905 (2014)

Conclusions

- REL kinematic effects depend on mass difference and lab energy
- REL results agree better with experimental data than NR results
- No REL effect observed for equal mass systems
- Equal mass results can be explained with rapidly decaying potential